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SPACE ENVIRONMENTAL EFFECTS ON SOLAR CELLS: LDEF AND OTHER FLIGHT TESTS*

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SUMMARY

This paper summarizes results of several experiments flown on the Long Duration Exposure Facility (LDEF) to examine the effects of the space environment on materials and technologies to be used in solar arrays. The various LDEF experiments are compared to each other as well as to other solar cell flight data published in the literature. Data on environmental effects such as atomic oxygen, ultraviolet light, micrometeroids and debris, and charged particles are discussed in detail.

The results from the LDEF experiments allow us to draw several conclusions. Atomic oxygen erodes unprotected silver interconnects, unprotected Kapton, and polymer cell covers, but certain dielectric coatings can protect both silver and Kapton. Cells that had wrap-around silver contacts sometimes showed erosion at the edges, but more recently developed wrap-through cells are not expected to have these problems. Micrometeroid and debris damage is limited to the area close to the impact, and microsheet covers provide the cells with some protection. Damage from charged particles was as predicted, and the cell covers provided adequate protection. In general, silicon cells with microsheet covers showed very little degradation, and solar modules showed less than 3% degradation, except when mechanically damaged. The solar cell choices for the Space Station solar array are supported by the data from LDEF.

INTRODUCTION

Several experiments were flown on the LDEF to examine the effects of the space environment on materials and technologies to be used in solar arrays. Although a great deal of work has gone into analyzing these experiments and drawing conclusions, the experiments were conducted by a variety of organizations and published in separate papers. In this paper, the published data are summarized and the various LDEF experiments are compared to each other as well as to other solar cell flight data published in the literature. This information can provide designers of new solar arrays with data on specific environmental effects that might apply to their spacecraft's orbit without requiring extensive literature searches.

This paper begins with a description of the various experiments flown on LDEF, as well as other flight data mentioned. A section on how solar cell measurements are made follows. Data on environmental effects such as atomic oxygen, ultraviolet light, micrometeroids and debris, and charged particles are then covered. Finally, future flights are described and conclusions are drawn.

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FLIGHT EXPERIMENTS

Table 1 presents a list of the experiments on LDEF that involved solar cells or solar arrays. Experiment S0014, the Advanced Photovoltaic Experiment (APEX) had active on-orbit monitoring of some of its cells for the first 325 days of the 69 month mission, and covered a large variety of cell types[1]. Experiment A0171, the Solar Array Materials Passive LDEF Experiment (SAMPLE) contained a variety of experiments with no active sampling. Unfortunately, due to the unexpected length of the mission, some of the polyimide substrates were eroded by atomic oxygen, and several pieces of the experiment were lost. SAMPLE was used to test different types of cells[2] and different types of cell covers[3]. Similar experiments were flown on M0003-4[4], and complete results are expected to be published soon. Two other experiments had solar modules to power non-solar experiments: the LDEF Heat Pipe Power System (S1001)[5], and the Space Plasma High Voltage Drainage Experiment (A0054)[6]. These experiments were useful because they provide data from actual working modules. Calculations of atomic oxygen fluence and solar ultraviolet irradiation exposure for the LDEF mission are given for each experiment in Table 2.

Other data discussed in this paper come from Space Shuttle flights STS-5 and STS-41, LIPS, Hughes, Space Systems/Loral, CRRES/HESP and the Hubble Space Telescope.

Table 1. List of solar cell experiments on LDEF.

Principal Investigator	Type of Cells	Number of Cells	Experiment/Description
NASA LeRC - D. Brinker	Si, GaAs	155	S0014 - Advanced Photovoltaic Experiment (APEX) [1]
NASA MSFC - A. Whitaker L. Young	Si	4 modules & 5 cells	A0171 - Solar Array Materials Passive LDEF Experiment (SAMPLE) [2]
NASA LeRC - D. Brinker	Si	20	A0171 - Solar Array Materials Passive LDEF Experiment [1]
JPL - P. Stella	Si	30	A0171 - Solar Array Materials Passive LDEF Experiment [3]
NASA GSFC - E. Gaddy	Si	45	A0171 - Solar Array Materials Passive LDEF Experiment
Wright Pat AFB - T. Trumble	Si, GaAs	70	M0003-4 - Advanced Solar Cell and Coverglass Analysis [4]
NASA GSFC - S. Tiller	Si	4 arrays	S1001 - LDEF Heat Pipe Power System [5]
MBB - L. Preuss	Si	3	S1002 - Evaluation of Thermal Control Coatings and Solar Cells
TRW - J. Yaung	Si	12	A0054 - Space Plasma High Voltage Experiment [6]

Table 2. Atomic oxygen fluence and solar UV radiation exposure for solar cell experiments on LDEF.

Experiment/Description	Atomic Oxygen Fluence (atoms/cm^3)	Solar ultraviolet irradiation (equivalent sun hours)
S0014 - Advanced Photovoltaic Experiment (APEX)	8.99×10^{21}	11,200
A0171 - Solar Array Materials Passive LDEF Experiment (SAMPLE)	7.15×10^{21}	9,400
M0003-4 - Advanced Solar Cell and Coverglass Analysis	8.99×10^{21} (leading) 1.32×10^{17} (trailing)	11,200 (leading) 11,100 (trailing)
S1001 - LDEF Heat Pipe Power System	4.59×10^{20}	14,500
S1002 - Evaluation of Thermal Control Coatings and Solar Cells	1.32×10^{17}	11,100
A0054 - Space Plasma High Voltage Experiment	8.43×10^{21} (leading) 2.31×10^{5} (trailing)	10,700 (leading) 10,500 (trailing)

SOLAR CELL MEASUREMENT

Solar cell efficiencies are measured from a current-voltage curve, where the voltage is swept from zero to its highest value at open circuit conditions (V_{oc}) and the current is measured from its highest value at short circuit conditions (I_{sc}) down to zero. Since the power of the cell is the voltage times the current, there is a value of voltage and current where the power is at its maximum. At this maximum power point, the fill factor (FF) is defined as

$$\text{Max. power} = V_{mp} I_{mp} = FF\, V_{oc} I_{sc}$$

where V_{mp} and I_{mp} are the maximum power point voltage and current. A sample current-voltage curve is shown in Figure 1.

It is difficult to extract relevant information by measuring V_{mp} and I_{mp}, whereas V_{oc}, I_{sc}, and FF correspond directly to physical properties of the cells. By comparing the V_{oc}, I_{sc}, and FF of a cell before and after a flight, it is often possible to diagnose the physical cause of any change. I_{sc} is proportional to the number of photons converted into electron-hole pairs that are successfully collected. If there is a drop in I_{sc} and a slight drop in V_{oc}, then this is caused by non-optimum light collection, and implies that there was added darkening or shading. If there is a drop in FF only, then the series resistance has increased, which means that a structure that is used to carry current -- such as cell gridlines or cell interconnects -- has been damaged. If there is both a drop in FF and V_{oc}, then shunt resistance has decreased, which means that a new conductive path has been created between the positive and negative contacts of the solar cell. This generally occurs when the semiconductor junction has been physically damaged, which can be caused by a micrometeroid/debris impact or by high energy protons. Figure 2 shows a circuit schematic for series and shunt resistance.

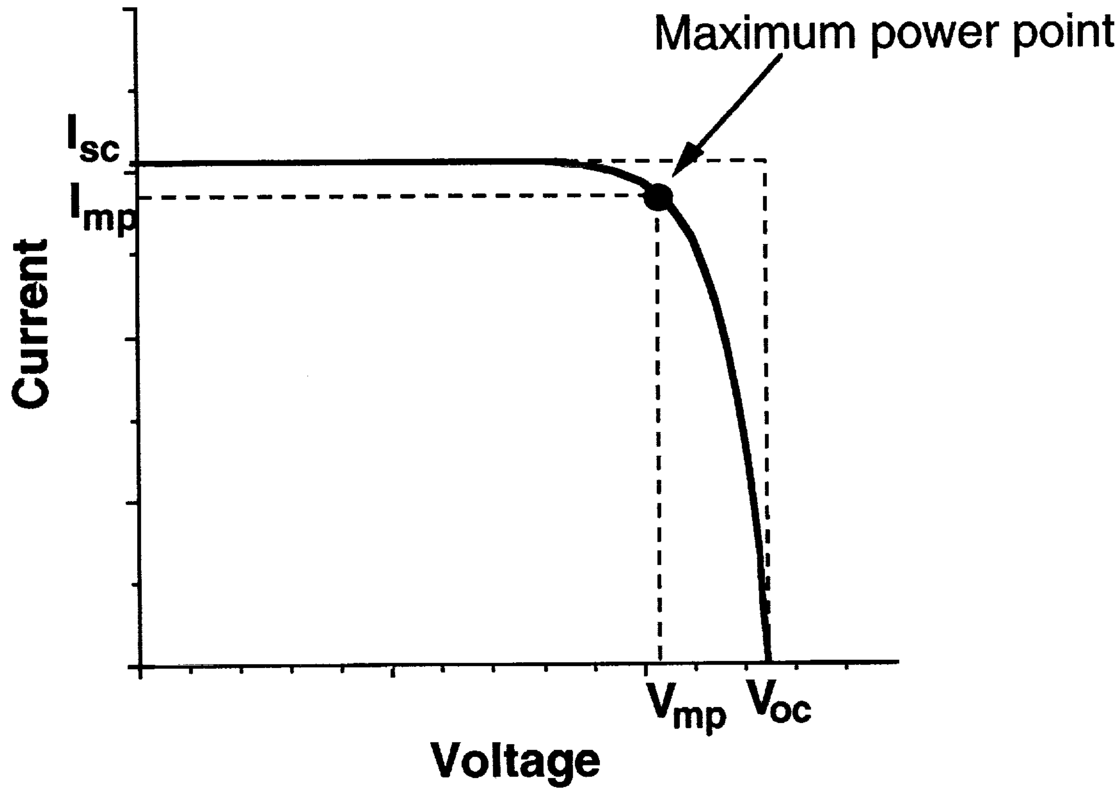

Figure 1. A sample solar cell current-voltage curve.

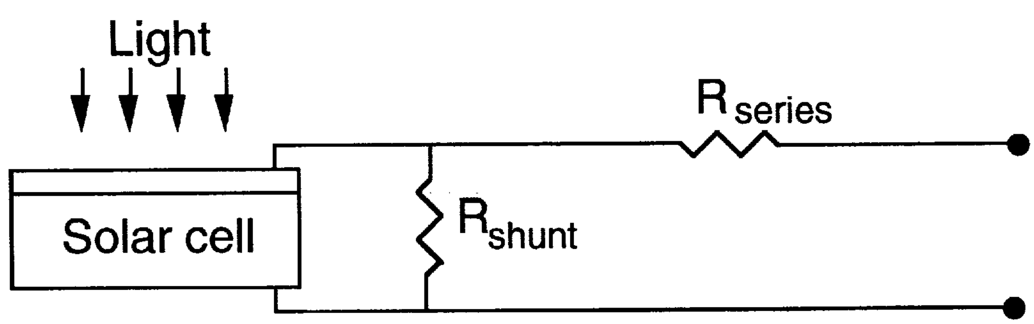

Figure 2. A circuit schematic showing the effects of series and shunt resistance.

ENVIRONMENTAL EFFECTS

Atomic Oxygen

Atomic oxygen is known to erode several materials that are often used in solar cell panels. In particular, the metal interconnects, the metal on the solar cells, the solar cell covers, and parts made of Kapton have all experienced atomic oxygen erosion. This section discusses each of these effects in detail.

Of particular importance is silver, which often is used as an interconnect material. Considerable data is available on these interconnects. On LDEF, silver ribbon was eroded when the flat side was to ram, but not when it was perpendicular to ram[1]. An Intelsat experiment on

Space Shuttle flight STS-41 investigated the erosion of silver interconnects[7]. From this experiment, an erosion rate for silver interconnects was calculated to be of 1.0 μm per 10^{20} atoms/cm^2. Intelsat also found that the back of the interconnect loop was oxidized due to atomic oxygen reflection. Silver that was coated with silicon nitride, silicon dioxide, and aluminum oxide was adequately protected. An earlier experiment on Space Shuttle flight STS-5 showed that coatings of aluminum, gold and palladium were inadequate to protect the silver[8]. Other silver results from Space Shuttle flights are discussed in reference [9].

The SAMPLE experiment on LDEF contained interconnects of rolled copper that were protected by Kapton, and no noticeable degradation was observed[2]. Similarly, measurements of the LDEF thermal blanket grounding straps showed that although copper oxidized in the LDEF orbit, the copper oxide was limited to less that 600 Å[10].

Certain cells carried on the LDEF SAMPLE and APEX experiment were "wrap-around" cells. Since it is simpler to make a module where both the positive and negative contacts of the cell are on the back side, the front contact of these cells wrapped around the cell edges and then continued on to the back, where contact is made. On the SAMPLE experiment, significant loss of silver on the edges of these cells was observed[2]. This corresponded to a loss in fill factor from an increased series resistance. When the current-voltage curves were measured while the edge of the wafer was bridged over, the fill factor and efficiency returned to near their beginning-of-life values. The modern version of the wrap-around cell is called "wrap-through," and there is a hole in the center of the cell where the front contact wraps through to the back. Since the center of the cell is well-protected by the coverglass, wrap-through cells are not expected to have this problem.

On the APEX experiment, the silicon cells made by Applied Solar Energy Corporation showed FF degradation for both the wrap-around cells (2% loss) and their conventional cells (6-18% loss)[1]. In this experiment, the wrap-around edges were protected, and the reason for the drop in fill factor is unknown.

Atomic oxygen can also affect the solar cell covers. The combined effects of atomic oxygen and ultraviolet light on LDEF will be discussed in a later section. LDEF experiment M0003-4 studied the effects of atomic oxygen on magnesium fluoride (MgF_2), which is sometimes used as an anti-reflection coating on solar cell covers[4]. Data suggests that MgF_2 loses fluorine and converts to MgO, which has a higher index of refraction, and therefore lessens the antireflective properties. Similarly, ThF_2 also appears to lose fluorine. These effects are still being studied.

LDEF experiments using Kapton with coatings of SiO_2 and Al_2O_3 show that these coatings adequately protect the Kapton from atomic oxygen[11]. However, cracks in the coating will lead to undercutting of the Kapton. Kapton used in the solar array on Space Station Freedom will see an atomic oxygen exposure that sweeps across various angles as the array tracks the sun. Laboratory and computer simulations show that this is expected to affect the undercutting profile[12].

Ultraviolet Light

Although ultraviolet light does not generally affect solar cells, it can reduce the amount of light that strikes the cell by either darkening an optical material or by creating and/or fixing films of contamination. In addition, ultraviolet light and atomic oxygen can combine to create a stronger effect; the combined effects on solar cell covers will be discussed in a later section.

Adhesives (DC 93-500, DC Q3-6576 and DC 3-6527) were used on Vertical Junction solar cells that were flown on the Living Plume Experiment (LIPS); they showed a small degradation as predicted, and no measurable difference among the adhesive types[13]. Trailing edge glass samples on LDEF showed significantly reduced transmission due to a film of contamination[14]. However, any atomic oxygen exposure seems to reduce this contamination film down to a thickness that is optically insignificant.

Micrometeroids and Debris

One of the major sources of damages to solar cell panels is micrometeroid and debris impacts[15]. Solar cells on SAMPLE with various cell covers showed that polymer cell covers provide very little protection[3]. For cells with microsheet glass covers, impacts were limited in area, and sometimes the microsheet cover prevented the particle from hitting the cell itself. When the crater diameters were about 100 μm, 2-4% degradation in short circuit current was observed. Impacts that only created small craters in the coverslide resulted in no measurable change in efficiency[2]. Also, no measurable change was found in the strength of glass samples struck by debris on another LDEF experiment[16].

If the cell itself was damaged, the loss in current was proportional to the damaged area[1]. In some instances, there was a loss in fill factor from increased series resistance due to breakage of the cells' grids. Cells impacted by micrometeroids and debris can exhibit any of the three damage mechanisms discussed in the introduction: loss of optical conversion due to damaged covers, increase in series resistance due to grid damage, or decrease in shunt resistance due to junction damage.

Charged Particles

The high energy proton and electron environment for LDEF was very low compared to most other orbits. The effects from electrons are almost negligible, and the majority of damaging photons were absorbed in most coverglass materials. The only cells that were expected to experience a significant amount of charged particle damage were cells with no coverglass protection. Note that the Space Station environment may have higher exposure, given that its orbit's inclination is higher than that of LDEF.

Calculations were performed to predict the charged particle damage for silicon cells on LDEF[17]. Physitron calculated a 5x10 e^-/cm^2 1 MeV electron equivalent, which corresponded to a 20% degradation. This calculation matches well with measurements on silicon cells without a coverglass. Similarly, other calculations were performed by Hughes for their HS393 solar arrays in geosynchronous orbit, and they found good agreement with measurements[18].

Silicon solar cells on LDEF with no coverglass showed I_{sc} and V_{oc} damage, consistent with charged particle damage[1]. Cells without covers on SAMPLE had a 21% degradation, whereas those with covers were protected with no effect from cover type[2]. Charged particle effects are not always predictable: Space Systems/Loral found that their silicon back-surface field cells in geosynchronous orbit were damaged more by solar flares than expected, but that they showed surprisingly high annealing[19].

For gallium arsenide (GaAs) solar cells, those flown on LDEF without covers showed significant damage that varied with the cell's junction depth, which is as expected[1]. GaAs cells were very new when LDEF was launched, so more recent data is preferable. 30 days of data for a geosynchronous transfer orbit flight to test solar cells made of gallium arsenide (GaAs) and gallium arsenide grown on germanium (GaAs/Ge) showed that coverglass thickness has a large effect[20]. Coverglass thickness of 12 mil or higher makes a significant difference in reducing the damage. The new GaAs/Ge cells performed quite well.

Combined Effects on LDEF

This section details the overall effects on the various solar cell experiments on LDEF. There were two experiments on LDEF with working solar arrays: the Heat Pipe experiment, which had a space-end array[5], and the Space Plasma High Voltage Damage Experiment, which had leading and trailing edge solar modules[6]. The Heat Pipe Experiments space-side array showed 1.5-3% overall degradation due to the combined effects of radiation, cover adhesive darkening, and micrometeroid damage. The leading and trailing edge modules of the SP-HVDE showed less than 2% overall degradation, except for one module which was damaged by a micrometeroid/debris impact, and showed a 10% loss. The SAMPLE experiment had several modules, many of which were lost on flight or during the Space Shuttle recovery. The one surviving complete module, Module 5, was found in the Space Shuttle cargo bay. It showed a 32% loss as an array, but this may have been due to its fall in the cargo bay[2].

Other solar cell results are listed in this paragraph. Most cells with 6 mil coverslides on SAMPLE had a degradation of 5% to 9%[2]. No degradation was measured on two types of cells on APEX: a 10 Ω-cm Si cell with a TaO_2 anti-reflection coating and a 12 mil coverslide; and a 1 Ω-cm Si cell with a 30 mil coverslide[1]. One GaAs cell flown on APEX with a 12 mil coverslide started at 16% efficient, but showed a surprisingly high 10% loss. Cells with polymer covers on APEX showed a current degradation (due to darkening) or a decrease in shunt resistance (reason unknown)[2]. Two cells were flown on SAMPLE with solar concentrators designed for 2X, although flight data showed that the concentration was actually 1.6X[2]. Over time, atomic oxygen eroded away the concentrator material, which was Kapton and Mylar, from the back side.

SAMPLE contained a very thorough experiment on solar cell covers[3]. Solar cells were covered with a variety of materials, including standard cerium-doped microsheet and a number of experimental polymer coatings. The short circuit current was measured before and after exposure to look for changes in the cover's transmission. Cells covered with cerium-doped microsheet showed the smallest change (3% loss). FEP Teflon had a darkened top surface (22% loss). Soft silicone coatings exhibited crazing and some loss near the cell edge (13% loss). Hard coat silicone showed crazing, flaking, and close to complete removal (17% loss). Cells covered with polyimide silicon co-polymer coating maintained a high current, but the reason is that it was largely removed (3% loss). GE x-76 polyimide was also significantly removed (8% loss). The conclusion of this experiment is that a quality polymer replacement has not been demonstrated, and that microsheet works quite well as a protective cover.

FUTURE FLIGHTS

The largest solar cell array to be flown in the near future is for Space Station. A description of the array is given in references [21] and [22]. The solar cells will be silicon, with a 10 Ω-cm base resistivity, 8 cm x 8 cm square, 0.0203 cm thick, with a wrap-through contact. There is a dual anti-reflection coating and a (p+) back surface field. The efficiency is 14.2%. The cover is a ceria-doped microsheet, 5 mil thick, with a UV-reflective coating. The interconnects are made of copper.

The results of LDEF suggest that these are good choices. Although this exact type of cell was not flown on LDEF, similar silicon cells performed well, and the wrap-through contact should avoid the problems that some of the wrap-around cells had on LDEF. The cover should protect the cells adequately from charged particles, and the UV-reflective coating does not contain MgF_2[23], so there should be no problem with conversion to MgO. Copper is a good choice for interconnects, since it will not be eroded in the same way as silver.

Although the Space Station orbit will have a similar altitude to the LDEF orbit, the new inclination is planned to be 57° as opposed to 28° for LDEF. This will result in an environment with a higher charged particle exposure that is very sensitive to altitude. The 5 mil coverglass will absorb protons of energy less than 4 MeV; the number of protons with energy greater than 4 MeV is expected to be higher by a factor of 2 to 8 at a 60° inclination, depending on the altitude[24]. Only the very low energy electrons will be affected by the coverglass; the total number of electrons is expected to be higher by a factor of 2 to 10 at a 60° inclination, depending on the altitude[24].

Other recent solar technologies include the Hubble Space Telescope array, where the silver interconnects are replaced with molybdenum, except where they are welded[25]. Silver plated molybdenum and silver plated Invar are now fairly common materials for interconnects. Cells made of gallium arsenide grown on germanium are gaining acceptance as having many advantages over silicon: higher efficiency, better charged particle resistance, and better temperature coefficient (i.e., the efficiency does not drop as much as the cell temperature rises). Even higher charged particle resistance can be obtained by using cells made of indium phosphide (InP). InP cells that flew in a polar orbit with only 2 mil coverglass showed very little degradation, despite a high radiation environment[26]. Multijunction cells have the potential for extremely high efficiency[27]. New materials are also being developed for solar cell covers, including new types of teflon and new protective coatings for silicone.

Future LDEF solar cell activity includes: the organization and publication of the solar cell results from experiment M0003-4 (Advanced Solar Cell and Coverglass Analysis); further research into the MgF_2 coating effect; and completing the testing of the cells on SAMPLE. The Photovoltaic Array Space Power Plus experiment (PASP+) is scheduled to be launched in 1994. This satellite contains a large variety of new solar cell technologies, including new thin films, concentrator modules, and multijunction cells. Further flights are expected using GaAs/Ge and InP cells.

CONCLUSIONS

This survey of space environmental effects on solar cells covered a wide range of flights. The conclusions from LDEF data can be listed as follows:

- Atomic oxygen erodes unprotected silver interconnects, unprotected Kapton, and polymer cell covers. Coatings can protect both silver and Kapton.
- Cells with wrap-around silver contacts sometimes showed erosion at the edges, but modern wrap-through cells are not expected to have these problems.
- Micrometeroid and debris damage is limited to the area close to the impact. Microsheet covers provide the cells with some protection.
- Damage from charged particles was as predicted. Covers provide adequate protection.
- In general, silicon cells with microsheet covers showed very little degradation.
- Solar modules showed less than 3% degradation, except when mechanically damaged.
- LDEF data supports solar cell choices for Space Station.

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